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Storage systems for Building-Integrated Photovoltaic (BIPV) and Building-Integrated Photovoltaic/Thermal (BIPVT) installations: Environmental profile and other aspects

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ABSTRACT

In recent years there has been an increasing interest in Building-Integrated Photovoltaic (BIPV) and Building-Integrated Photovoltaic/Thermal (BIPVT) systems since they produce clean energy and replace conventional building envelope materials. By taking into account that storage is a key factor in the effective use of renewable energy, the present article is an overview about storage systems which are appropriate for BIPV and BIPVT applications. The literature review shows that there are multiple storage solutions, based on different kinds of materials (batteries, Phase Change Material (PCM) components, etc.). In terms of BIPV and BIPVT with batteries or PCMs or water tanks as storage systems, most of the installations are non-concentrating, façade- or roof-integrated, water- or air-based (in the case of BIPVT) and include silicon-based PV cells, lead-acid or lithium-ion batteries, paraffin- or salt-based PCMs. Regarding parameters that affect the environmental profile of storage systems, in the case of batteries critical factors such as material manufacturing, accidental release of electrolytes, inhalation toxicity, flammable elements, degradation and end-of-life management play a pivotal role. Regarding PCMs, there are some materials that are corrosive and present fire-safety issues as well as high toxicity in terms of human health and ecosystems. Concerning water storage tanks, based on certain studies about tanks with volumes of 300 L and 600 L, their impacts range from 5.9 to 11.7 GJ_{prim} and from

0.3 to 1.0 t $CO_{2.eq}$. Finally, it should be noted that additional storage options such as Trombe walls, pebble beds and nanotechnologies are critically discussed. The contribution of the present article to the existing literature is associated with the fact that it presents a critical review about storage devices in the case of BIPV and BIPVT applications, by placing emphasis on the environmental profile of certain storage materials.

Keywords: Storage materials; Building-Integrated Photovoltaic (BIPV); Building-Integrated Photovoltaic/Thermal (BIPVT); Life Cycle Assessment (LCA); CO_2 emissions, embodied energy; Human toxicity, ecotoxicity

1. INTRODUCTION

Among renewable energy sources, solar energy is essential and offers multiple types of systems, for instance for building applications. The systems that are usually adopted in the building sector are Photovoltaic (PV) panels and solar thermal collectors (Kalogirou et al., 2014). Solar systems show high environmental performance in countries with high solar irradiation such as Spain (Pardo et al., 2019; Stamford and Azapagic, 2019).

By taking into account environmental concerns such as CO_2 emissions and fossil-fuel energy consumption e.g. in the building sector (Sarkodie and Strezo, 2019), in the past few years a whole host of solar systems which are integrated into the building have been studied. These systems are known as Building-Integrated (BI) and

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ABBREVIATIONS: AHU: Air Handling Unit; BA: Building-Added; BA PVT: Building-Added Photovoltaic/Thermal; BI: Building-Integrated; BICPV: Building-Integrated Concentrating Photovoltaic; BICPVT: Building-Integrated Concentrating Photovoltaic/Thermal; BIPV: Building-Integrated Photovoltaic; BIPVT: Building-Integrated Photovoltaic/Thermal; BIST: Building-integrated Solar Thermal; CIS: Copper indium diselenide; CML 2001: CML 2001 method; $CO_{2.eq}$: $CO_{2.equivalent}$; CPV: Concentrating Photovoltaic; CPVT: Concentrating Photovoltaic/Thermal; CTU_e: Comparative toxic unit for ecosystems; CTU_h: Comparative toxic unit for humans; DALY: Disability-adjusted life years; Eco-indicator 99: Eco-indicator 99 method; EPBT: Energy Payback Time; IPCC 2013 GWP 100a: Method which shows Global Warming Potential (GWP) in a time horizon of 100 years; GHG: Greenhouse Gas; GJ_{prim}: $GJ_{primary}$; LCA: Life Cycle Assessment; PBT: Payback Time; PCM: Phase Change Material; PV: Photovoltaic; PVT: Photovoltaic/Thermal; PVT/air: Photovoltaic/Thermal with air as working fluid; PVT/water: Photovoltaic/Thermal with water as working fluid; ReCiPe: ReCiPe method; (species.yr): Loss of species over a certain area (during a certain time); TE-AD: Thermoelectric Air-cooling Duct; USEtox: USEtox method have double function: 1) building components, 2) elements which produce energy. This specific category includes multiple configurations: Building-Integrated Solar Thermal (BIST), Building-Integrated Photovoltaic (BIPV), Building-Integrated Photovoltaic/Thermal (BIPVT), Building-Integrated Concentrating Photovoltaic (BICPV), Building-Integrated Concentrating Photovoltaic/Thermal (BICPVT), etc. It should be highlighted that the BI solar systems replace a building element (façade, roof, etc.) and are not added on the building as the Building-Added (BA) ones (Lamnatou and Chemisana, 2017). In the literature about BI solar systems, multiple advantages of these configurations such as high aesthetic value, replacement of traditional building components (Kalogirou et al., 2014; Lamnatou and Chemisana, 2017) and positive contribution in the case of nearly zero-energy buildings (Tripanagnostopoulos, 2014; Moldovan et al., 2016; Palacios-Jaimes et al., 2017; Athienitis et al., 2017) have been highlighted. BIPV systems represent an expansive market and are related to energy savings in the building sector and nearly zero-energy buildings. In the frame of BIPV market, key parameters such as flexibility in design, aesthetics, long-term reliability, legal regulations, smart energy management and cost effectiveness play a pivotal role (Source: Cordis).

It is known that for the development of efficient renewable-energy systems, long-term and short-term storage is a critical issue mainly due to the intermittent nature of renewable energy sources such as solar energy. In the literature about storage systems, review articles that present an overview about multiple kinds of storage devices can be found. For example, Argyrou et al. (2018) conducted a literature review about energy storage for electricity generation for small- and large-scale applications. Sarbu and Dorca (2018) presented an overview about the development of latent-heat storage systems with emphasis on heat transfer and techniques in order to achieve effective charging/discharging of the latent heat in the frame of Phase Change Material (PCM) applications. Tarkowski (2019) discussed characteristics and prospects of underground hydrogen storage.

On the other hand, in the literature about BA PVT, BIPV and BIPVT systems, review articles have been presented. For instance, Charalambous et al. (2007) conducted a review about Photovoltaic/Thermal (PVT) collectors, discussing the specific case of BIPV systems. Another review article, about double-skin façades and BIPV heat transfer, has been presented by Agathokleous and Kalogirou (2016). Moreover, Lamnatou and Chemisana (2017) and Jia et al. (2019) conducted critical reviews about PVT systems, including BIPV and BIPVT configurations.

In light of the issues mentioned above, it can be seen that there is a need for reviews that present storage solutions for BI solar systems, with emphasis on the environmental impacts of different kinds of storage components. The present article is an overview about multiple storage devices appropriate for BIPV and BIPVT systems, focusing on environmental issues (embodied energy, embodied carbon, toxicity, etc.) of certain storage materials. More analytically, the structure of the present paper is as follows:

- Storage systems: A general overview.
- Presentation of multiple BIPV and BIPVT configurations with different storage options: Batteries, PCMs, water storage tanks, Trombe walls, etc.
- Discussion about different kinds of storage systems with emphasis on their environmental profile: Batteries, PCMs, water storage tanks. Issues about the toxicity of certain materials.

The innovation of the present article is related to the fact that in the literature there is a lack of reviews about storage options in the case of BIPV and BIPVT systems, placing emphasis on storage-device environmental profile. Given the fact that certain storage materials present environmental issues such as human toxicity and ecotoxicity, a discussion about key environmental aspects is provided. By taking into account that: 1) in recent years there has been a growing interest in BI solar systems, 2) storage components are essential parts of renewable-energy power generation, the present study offers useful information from different points of view (technical, environmental).

2. LITERATURE REVIEW

2.1. STORAGE SYSTEMS: A GENERAL OVERVIEW

In the present subsection, an overview about different kinds of storage devices is presented. In Figure 1, a schematic with a general classification is illustrated. An additional categorisation for storage systems could be as follows: 1) active, 2) passive, 3) hybrid.

From Figure 1 it can be seen that there is a whole host of storage solutions based on different kinds of materials (organic PCM, inorganic PCM, batteries, nanotechnologies, etc.). Certain of the storage options which are shown in Figure 1 can be adopted in the frame of BIPV and BIPVT applications.

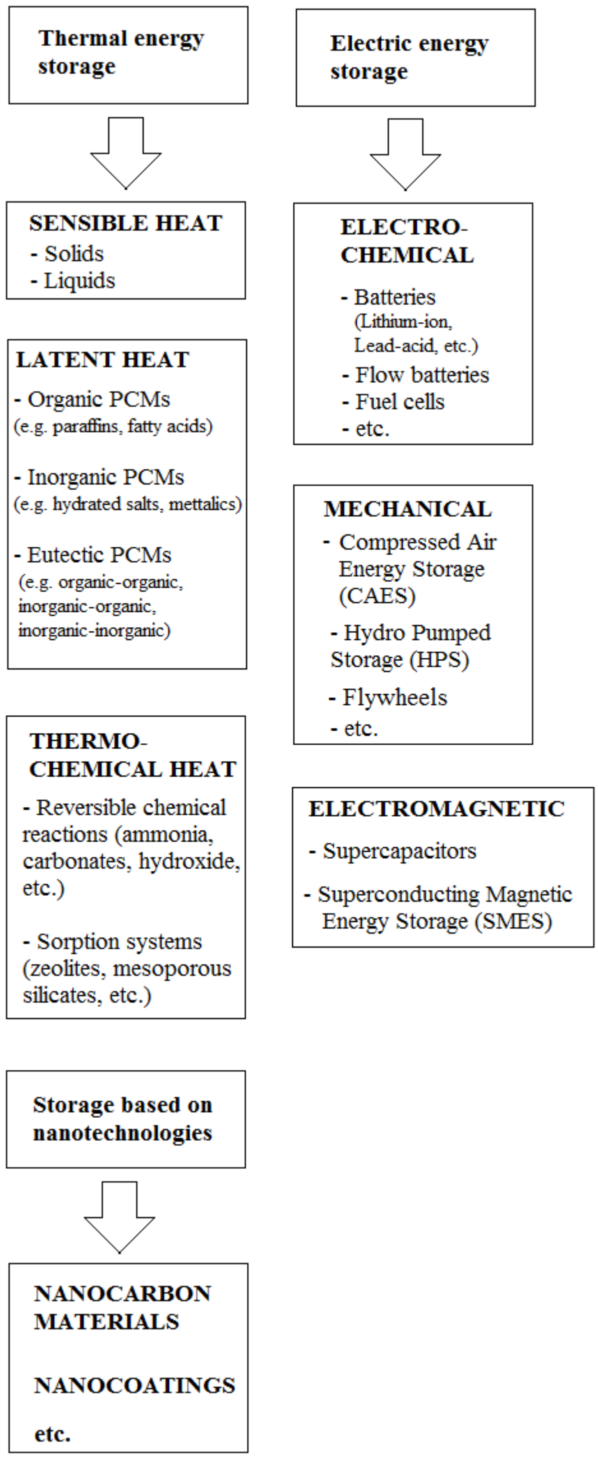

Figure 1. A schematic with multiple types of storage systems.

In subsection 2.2.1, a general overview about different BIPV and BIPVT configurations is presented. Having as criteria storage devices/materials appropriate for BIPV and BIPVT applications, in subsections 2.2.2-2.2.7 various storage solutions are discussed. The classification is mainly based on the materials of the storage devices. However, in certain cases, an additional categorisation, ¨non-concentrating vs. concentrating systems¨, has been included. Finally, in section 2.3, several factors related to different kinds of storage solutions, with emphasis on environmental issues, are analysed.

2.2. PRESENTATION OF MULTIPLE BIPV and BIPVT SYSTEMS WITH DIFFERENT STORAGE OPTIONS

2.2.1. An overview about different types of BIPV and BIPVT systems

The present subsection presents a general picture about several BIPV and BIPVT configurations that have been developed and studied:

- Semitransparent PVs for façades (Xu et al., 2014).
- Two-inlet air-based BIPVT (Yang and Athienitis, 2015).
- Façade-integrated PVs combined with glazing (Cuce et al., 2015).
- Solar honeycomb façade with integrated PV cells (Brandl et al., 2016).
- Roof-integrated PVT with aluminium/high-density polyethylene functionally graded materials (Chen et al., 2016; Chen and Yin, 2016).
- Active BIPV thermoelectric wall system (Luo et al., 2016).
- BIPVT for different types of building envelopes (Buonomano et al., 2016).
- BIPVT based on semitransparent PVs (Gupta et al., 2017).
- Refractive cylindrical Concentrating Photovoltaic/Thermal (CPVT) module with PV cells immersed in deionised water or isopropyl alcohol, appropriate for façade-integrated applications (Moreno et al., 2018; Riverola et al., 2018).
- Naturally ventilated BIPVT/air (Agathokleous et al., 2018; Agathokleous and Kalogirou, 2018a; Agathokleous and Kalogirou, 2018b).

- Low-concentrating BIPV with asymmetric compound parabolic concentrator (Li et al., 2018).
- Façade-integrated Concentrating Photovoltaic (CPV) system with Fresnel lens as concentrator (Zhu et al., 2018).
- BICPV configurations with holographic solar concentrators (Marín-Sáez et al., 2019).
- BIPV systems based on organic PVs (Chemisana et al., 2019; Freitas et al., 2019).

In addition to the configurations mentioned above, in the review articles by Charalambous et al. (2007), Norton et al. (2011), Daghigh et al. (2011), Chow et al. (2012), Agathokleous and Kalogirou (2016), Besheer et al. (2016), Lamnatou and Chemisana (2017), Biyik et al. (2017), diverse PV and PVT configurations, including BIPV and BIPVT, can be found.

2.2.2. BIPV and BIPVT with battery storage: Non-concentrating and concentrating systems

With respect to non-concentrating configurations, Pal et al. (2016) presented a study about PV windows with semitransparent amorphous-silicon thin-film PV cells for building envelopes in Finland. It was noted that the energy matching could be enhanced by installing PV glazing only on the south-oriented windows or by using battery storage. Moreover, Irshad et al. (2019) investigated a BIPV with battery storage and thermoelectric air cooling. The study included both economic and environmental issues based on Life Cycle Assessment (LCA). In Figure 2, a schematic of the BIPV configuration studied by Irshad et al. (2019) is illustrated.

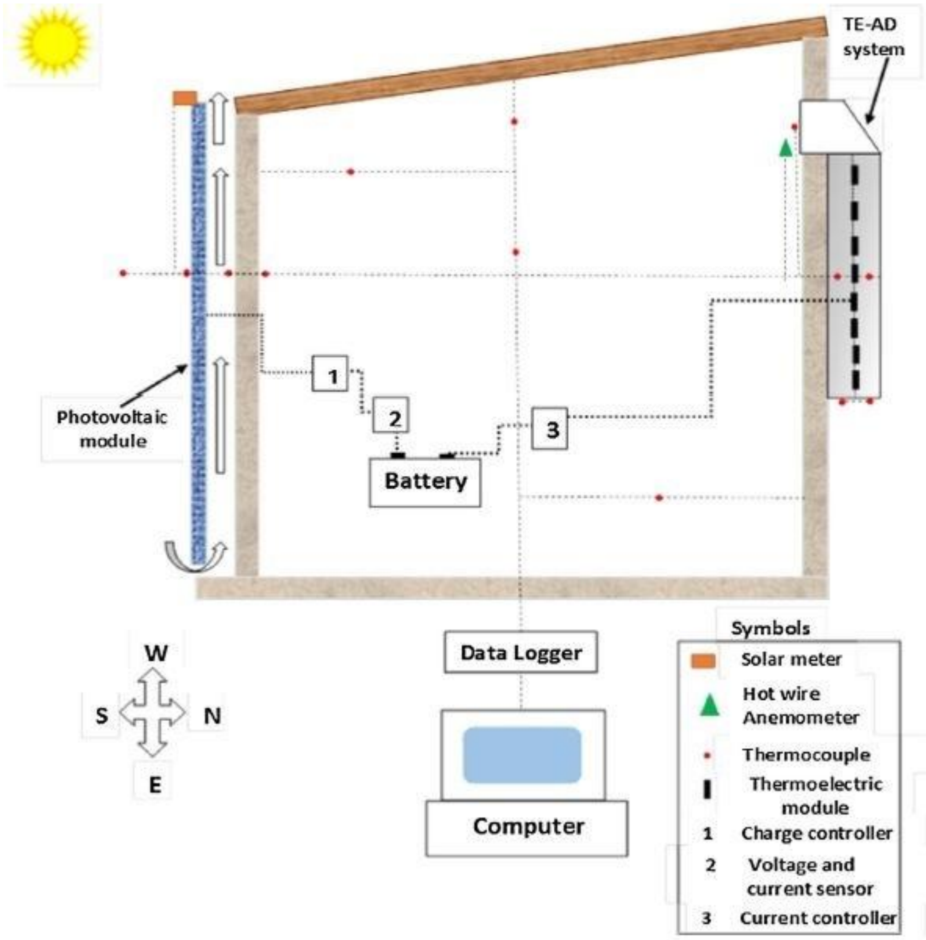

Figure 2. Schematic of a test room with BIPV, battery storage and Thermoelectric Air-cooling Duct (TE-AD) system studied by Irshad et al. (2019). Source: Irshad et al. (2019).

Regarding concentrating configurations, Menoufi et al. (2013) conducted an LCA about a BICPVT installation with reflectors as windows blinds. A comparison with a non-concentrating counterpart system was presented. The results verified that by replacing the conventional BIPV systems with the BICPV ones, there is a remarkable reduction in the environmental impact. Menoufi et al. (2013) did not include in the LCA storage devices but it was noted that the proposed solar system can work as grid-connected or stand-alone with batteries.

In Table 1, selected references about BIPV and BIPVT systems with battery storage can be found. From Table 1 it can be seen that:

- Most of the systems are non-concentrating and appropriate for façade- or roof-integrated applications.
- There are few investigations about BIPV configurations combined with smart-grid systems.
- In most of the BIPVT cases, the working fluid is water.
- The majority of the references include modelling and experimental/modelling studies.
- Different locations were examined: Europe, USA, China, Korea, Malaysia and India.
- Most of the PV panels are based on polycrystalline-silicon cells.
- The majority of the batteries are lead-acid and lithium-ion.
- Multiple factors such as battery aging, economic/environmental issues, battery capacity, energetic flexibility and combination of batteries with other types of storage systems were discussed.

Table 1. References about BIPV and BIPVT systems with battery storage.

Study	Type of system	Type of study	Location	Type of PV cells	Type of battery	Comments
Chow et al. (2008)	Non-concentrating BIPVT/water: Façade-integrated with storage tank and batteries	Experimental; Modelling	China	Polycrystalline silicon	Not directly stated	Electrical provisions of the PV panels: batteries, inverter, connections to the electrical appliances
Menoufi et al. (2013)	Concentrating BIPVT/water: Façade-integrated	Modelling	Spain	Monocrystalline silicon	Not directly stated	The LCA study did not include storage systems but it was noted that the proposed configuration can work as grid-connected or as stand-alone with batteries
Sechilariu et al. (2013)	Non-concentrating BIPV with smart-grid communication	Experimental; Modelling	France	Not directly stated	Not directly stated	Regarding storage-operating mode modelling, storage-state-of-charge was utilised in order to indicate the battery

						storage level
Lee et al. (2015)	Non-concentrating BIPV: Dynamic façades	Modelling	USA	Polycrystalline silicon	Lead-acid	Decrements to the electric load were observed (due to on-site utilisation of PV production and battery storage during the daytime)
Wang et al. (2016a)	Non-concentrating heat-pipe BIPVT/water with PCM, batteries and water tank	Experimental	China	Polycrystalline silicon	Not directly stated	The electricity stored in the batteries is utilised, for instance, for the water pump or for the electrical devices of the buildings
Wang et al. (2016b)	Non-concentrating heat-pipe BIPVT/water: Potential of building integration (walls, roofs, balconies: residential buildings)	Experimental	China	Polycrystalline silicon	Not directly stated	Two parallel batteries were connected to the PVT panel and inverter
Oliveira (2016)	Non-concentrating BIPVT/air: Façade-integrated	Modelling	Europe	Monocrystalline silicon	Not directly stated	It was noted that an extension of the proposed system would include battery storage
Hwang et al. (2016)	Non-concentrating BIPV: Façade- or roof-integrated systems	Modelling	Korea	Crystalline silicon	Not directly stated	The charging/discharging of the batteries was evaluated
Abawi et al. (2016)	Non-concentrating BIPV: Façade-integrated PV panels combined with façade-integrated solar thermal collectors	Experimental; Modelling	Austria	Polycrystalline silicon; Amorphous (semitransparent)	Lead-acid	Battery aging was discussed; The system also includes a water tank connected with the solar thermal collectors
Pal et al. (2016)	Non-concentrating BIPV: Windows with semitransparent PV cells	Modelling	Finland	Amorphous-silicon thin-film	Not directly stated	The energy matching could be enhanced by using PV glazing only on the south-oriented windows or by adopting batteries
Buonomano et al. (2017)	Non-concentrating BIPVT/water: Roof-	Modelling	Italy	Polycrystalline silicon	Lead-acid	The capacity of the batteries was selected based on economic criteria

	integrated					
Yassin et al. (2017)	Non-concentrating BIPV: Roof-integrated	Modelling	Norway; India	Crystalline silicon (Norway); Polycrystalline silicon (India)	Lead-acid	The model evaluates ¨annual electricity bill vs. battery capacity interval¨ and indicates the optimum capacity for achieving the minimum annual electricity bill
Couty et al. (2017)	Non-concentrating BIPV: Façade-integrated	Experimental; Modelling	Switzerland	Monocrystalline silicon	Lithium-ion	If the battery is full, the overproduction is injected into the grid; If there is lack of energy, an algorithm selects between taking energy from the grid or from the battery, depending on factors such as grid carbon footprint and price of electricity
Lovati et al. (2019)	Non-concentrating BIPV: Façade- or roof-integrated systems	Modelling	Italy	Not directly stated	Lithium-ion	Batteries: 3 different capacities were examined
Aelenei et al. (2019)	Non-concentrating BIPV: Façade-integrated PV panels (the installation also includes a solar thermal system based on compound parabolic concentrators)	Modelling	Portugal	Polycrystalline silicon (South façade); Amorphous silicon (parking)	Lithium-ion	By means of the integration of battery energy storage systems with capacities varying from 13.5 kWh to 54 kWh, energetic flexibility was achieved
Irshad et al. (2019)	Non-concentrating BIPV: Thermoelectric air-cooling and PV wall system	Experimental; Modelling	Malaysia	Not directly stated	Not directly stated	The grid-connected thermoelectric air-cooling duct system presented 35.49 t reduction in CO_2 emissions (lifespan); Regarding the useful life of the batteries, a time period of 5 years was assumed
Aguacil et al. (2019)	Non-concentrating BIPV: Configurations for façade or roof integration	Modelling	Switzerland	Monocrystalline silicon	Lithium-ion	If the option of injecting electricity into the grid is difficult or impossible, batteries play a pivotal role

2.2.3. BIPV and BIPVT with PCM storage: Non-concentrating and concentrating systems

Regarding non-concentrating systems with PCMs, Favoino et al. (2016) investigated multifunctional façade modules. Outdoor experiments were conducted. The aim of the study was to overcome certain drawbacks of double-skin and advanced-integrated façades such as low thermal inertia and high window-to-wall ratio. In light of the issues mentioned above, Favoino et al. (2016) developed a façade-integrated solar system with the following characteristics:

- Combination of PV cells and solar thermal collector (both façade-integrated).
- Option for thermal storage in building envelope.
- Solar-gain management (in both opaque and transparent configurations).

Favoino et al. (2016) highlighted that PV modules combined with thermal energy storage offer an efficient solar-production management, facilitating the matching between energy generation and consumption. The proposed configuration includes three electric-heated foils powered by amorphous-silicon PV modules. The foils are between two PCM layers (active thermal energy storage). The two PCM layers have different peak melting temperatures (23 and 27^{o}C), depending on the season (Favoino et al., 2016). An additional study about a non-concentrating BIPV system with PCM has been presented by Hasan et al. (2010). Experiments with solar simulator were conducted. Different types of PCMs were examined: Paraffin wax (RT20), eutectic mixture of capric-lauric acid (C-L), eutectic mixture of capric-palmitic acid (C-P), pure salt hydrate ($CaCl_2 \cdot 6H_2O$) and the commercial blend SP22. Moreover, the PCMs were evaluated at three insolations. The findings showed that the salt hydrate has the highest decrease in temperature in most of the cases/insolations. In Figure 3, the experimental set up developed by Hasan et al. (2010) is illustrated.

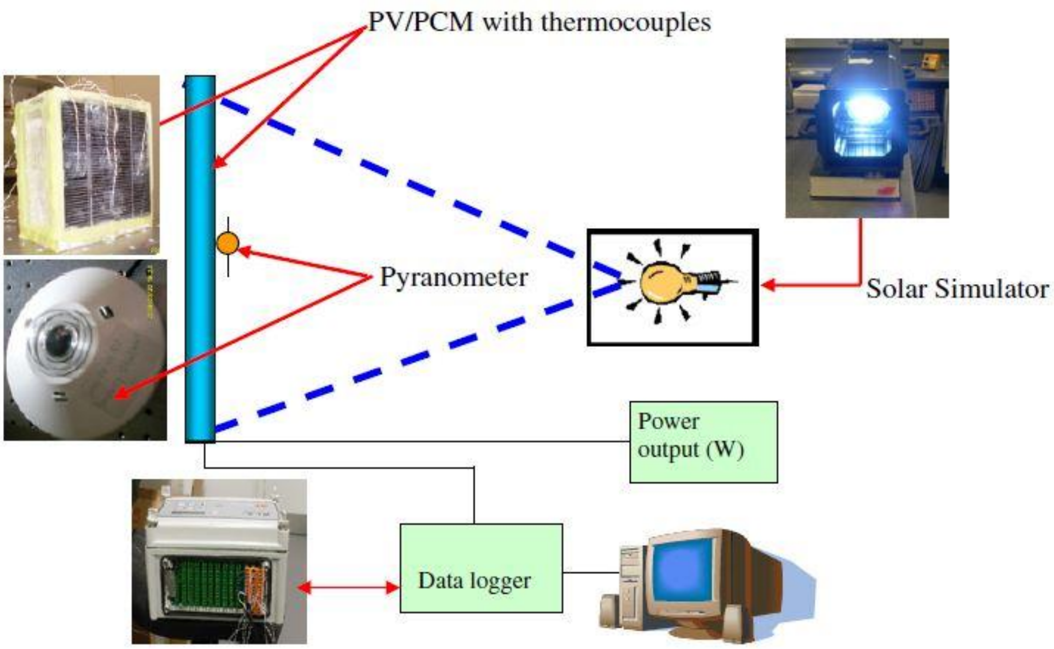

Figure 3. Schematic of the experimental BIPV/PCM setup developed by Hasan et al. (2010). Source: Hasan et al. (2010).

Concerning concentrating BIPV (or BIPVT) systems with PCMs, Sharma et al. (2016) proposed a low-concentrating BIPV installation with paraffin-wax PCM. The effect of the PCM component on PV electrical parameters was analysed. Experiments were conducted. It was noted that, as a future prospect, studies about economic and environmental issues of the proposed system are needed.

In Table 2, certain studies about BIPV and BIPVT with PCMs are presented. From Table 2 it can be seen that:

- A large majority of the PV systems are non-concentrating and appropriate for façade-integrated applications.
- Most of the PVT configurations are air-based.
- The majority of the studies are modelling or experimental/modelling.
- Different locations were examined: Europe, Canada, USA, Australia, etc.
- Most of the systems include silicon-based PV cells.

- The majority of the PCMs are paraffins or salts.
- Certain investigations evaluate PCM performance in terms of thermal regulation, PCM thermal mass and PV/PCM thermal conductivity.
- Some studies examine the temperature inside the air cavity between PV panel and PCM component.
- In relation to PV output and building energy consumption, the adoption of PCM offers benefits.

Table 2. References about BIPV and BIPVT systems with storage based on PCM components.

Study	Type of system	Type of study	Location	Type of PV cells	Type of PCM	Comments
Athienitis et al. (2005)	Double façades: Configurations with PCM, non-concentrating PV panels and air cavities	Experimental; Modelling	Canada	Not directly stated	Butyl stearate (absorbed in gypsum board)	A numerical model for the heat transfer in the PCM component was developed
Hasan et al. (2010)	Non-concentrating BIPV: Wall which includes PV panels and PCM	Experimental	Different cases were examined, including hot climates	Polycrystalline silicon	Paraffin wax (RT20); Eutectic mixture of capric-lauric acid (C-L); Eutectic mixture of capric-palmitic acid (C-P); Pure salt hydrate ($CaCl_2 \cdot 6H_2O$); Commercial blend (SP22)	The PCMs were examined at three insolations and it was found that PCM thermal-regulation performance is related to PCM thermal mass, PCM thermal conductivity, PV/PCM thermal conductivity
Hendricks and van Sark (2013)	Non-concentrating BIPV: PV/PCM system	Modelling	Netherlands; Spain	Silicon	Paraffin waxes	In comparison to other solutions for temperature regulation (e.g. forced air circulation), PV/PCM offers benefits

						(increased heat absorption, etc.)
Aelenei and Pereira (2013)	Non-concentrating BIPVT/air: BIPVT with PCM for façade-integration	Modelling	Portugal	Not directly stated	Butyl stearate (Athienitis et al., 1997)	BIPVT/PCM offers a reduction in the temperature inside the air cavity
Yin et al. (2013)	Non-concentrating BIPVT/water: Roof-integrated system with PCM	Experimental; Modelling	USA	Monocrystalline silicon	A mixture of salts	The proposed system fulfills the basic functions of a building envelope and produces energy for the building
Aelenei et al. (2014a)	Non-concentrating BIPVT/air: Façade-integrated PVT with PCM wall	Experimental; Modelling	Portugal	Polycrystalline silicon	PCM gypsum board	Thermal efficiency of the system: approximately 10%; Overall efficiency of the system (electrical and thermal): around 20%
Aelenei et al. (2014b)	Non-concentrating BIPVT/air: Façade-integrated PVT with PCM wall	Experimental; Modelling	Portugal	Polycrystalline silicon	PCM gypsum board	BIPVT/PCM shows higher cost comparing to a traditionally insulated brick wall but, if it is insulated, it is effective in reducing building energy demand
Xiang and Gan (2015)	Non-concentrating BIPVT/air: PV/PCM wall	Experimental; Modelling	UK	Monocrystalline silicon	Hydrated salt	PCM is effective in eliminating PV temperature increase; PCM heat can reduce building energy consumption
Machniewicz et al. (2015)	Non-concentrating BIPVT/air: Façade-integrated	Modelling	Central Europe	Thin-film CIS	Paraffin waxes: RT10HC, RT18HC, RT25HC,	The selection of the PCM specific transition temperature

	with PCM				RT35HC	should be based on the weather conditions of the location; Building orientation should also be considered
Favoino et al. (2016)	Non-concentrating BIPVT/air: Façade-integrated system with PCM	Experimental	Italy	Amorphous silicon	Use of two PCM layers with different peak melting temperatures	The combined effect ventilated cavity/PCM presents a dynamic behaviour; Modes: active or passive
Wang et al. (2016a)	Non-concentrating heat-pipe BIPVT/water with PCM, batteries and water tank	Experimental	China	Polycrystalline silicon	Paraffin, silica (GR52)	PCM and metal wires were placed in the space between the heat pipes and insulation
Indartono et al. (2016)	Non-concentrating PVs for roofs: BA systems were examined and the option of BIPV was discussed	Experimental	Indonesia	Monocrystalline silicon	Yellow petroleum jelly (vaselinum flavum)	The PVs with PCM presented lower surface temperature (in comparison to the PVs without PCM); Lower PV-panel temperature leads to higher PV power production
Lin et al. (2016)	Non-concentrating roof-integrated BIPVT/air system combined with PCM wall	Modelling	Australia	Not directly stated	Organic (RT18HC: paraffin) and inorganic (SP21E, SP24E: salt hydrates)	PCMs in building envelops offer reduction in indoor-temperature fluctuations
Sharma et al. (2016)	Concentrating BIPV	Experimental; Modelling	Different cases were examined	Crystalline silicon	Paraffin wax (RT42)	Building regulations, economic and environmental assessment would offer further development of the proposed

						system
Kibria et al. (2016)	Non-concentrating BIPV	Modelling	Saudi Arabia	Polycrystalline silicon	Paraffin-based	In terms of the PCM, 3 cases were examined: RT20, RT25, RT28HC
Bigaila and Athienitis (2017)	Non-concentrating BIPVT/air: Façade-integrated system with heat pump and PCM	Modelling	Canada	Silicon-based	The PCM layer includes shape-stabilised panels of paraffin wax suspended in an ethylene-based polymer	In certain cases, an electric-power-demand reduction of 14.5% was achieved
Pereira and Aelenei (2019)	Non-concentrating BIPVT/air: Façade-integrated system with PCM	Experimental; Modelling	Portugal	Polycrystalline silicon	PCM gypsum board	Optimisation variables: Air-cavity thickness, air flow velocity (within the air cavity), PCM latent heat, PCM-board thickness

2.2.4. BIPVT systems (or BIPV combined with solar thermal collectors) with water storage tanks: Non-concentrating and concentrating systems

Regarding non-concentrating BIPVT systems, Gautam and Andresen (2017) presented a model about a façade-integrated configuration with water as working fluid. A stratified storage tank with a uniform loss of 1 W/K at 50^{o}C was considered. Moreover, Li et al. (2015a) proposed a BIPVT system which combines PVs with unglazed transpired solar collectors. The installation utilises a water tank as heat source for radiant floor heating. In Figure 4, a diagram with the components (BIPVT, heat pump, storage tank, etc.) of the system studied by Li et al. (2015a) is illustrated.

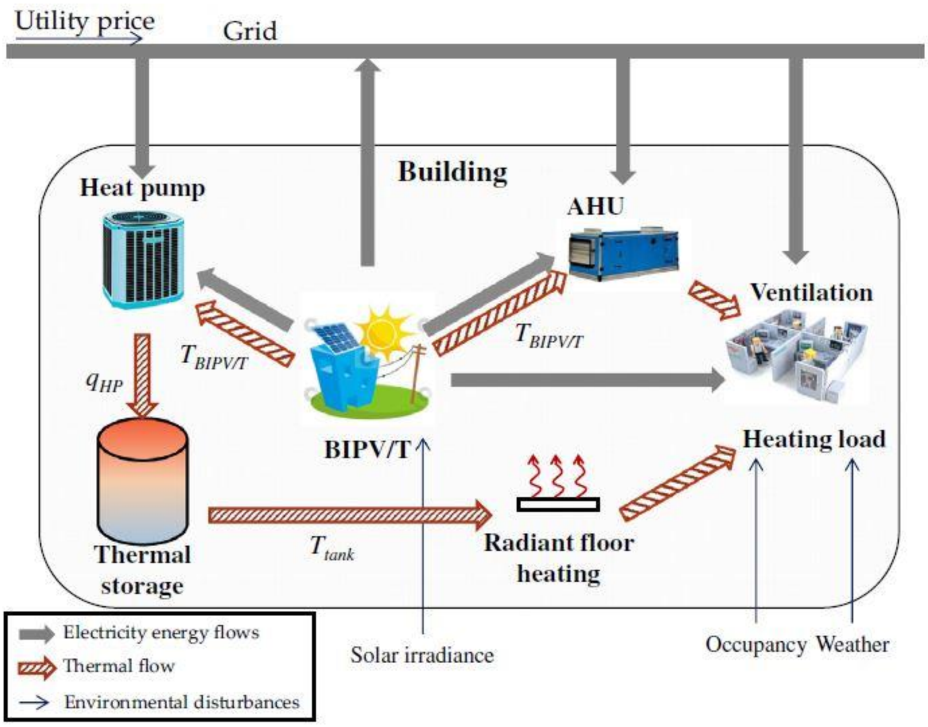

Figure 4. Diagram of the BIPVT installation studied by Li et al. (2015a): BIPVT panels with transpired collectors, Air Handling Unit (AHU), ventilation, heat pump, storage tank and radiant floor heating. Source: Li et al. (2015a).

With respect to concentrating BIPVT systems, Li et al. (2015b) investigated an air-gap-lens-walled compound parabolic concentrator combined with PVT/water, appropriate for BI applications. An overall system efficiency of 65.5% was found. The system includes a water storage tank.

In Table 3, selected literature studies about BIPVT systems (or BIPV combined with solar thermal collectors) with water storage tanks can be found. From Table 3 it can be noted that:

- Certain systems combine storage tanks with heat exchangers, heat pumps and auxiliary heaters.
- Some studies place emphasis on energy savings and environmental benefits (reduction in Greenhouse Gas (GHG) emissions, etc.) whereas other

investigations focus on optimisation (e.g. in terms of the dimensions of the storage tank).

- Issues such as the effect of solar radiation and water flow rate on water-tank temperature were examined.
- Some references include evaluation of water storage tanks in relation to building energy needs and functions.
- With respect to the type of systems, the majority of the studies are about non-concentrating configurations appropriate for façade- and roof-integrated applications and PVT/water (in the case of PVT).
- Regarding the type of the studies, a large majority of the investigations are modelling and modelling/experimental.
- Concerning locations/climatic conditions, different cases (Europe, Canada, USA, China, Korea, etc.) were examined.
- In terms of PV-cell type, the majority of the studies include silicon-based PV cells.

Table 3. References about BIPVT systems (or BIPV combined with solar thermal collectors) with water storage tanks.

Study / year	**Type of system**	**Type of study**	**Location**	**Type of PV cells**	**Information about the water storage tank**	**Comments**
Chow et al. (2008)	Non-concentrating BIPVT/water: Façade-integrated with storage tank and batteries	Experimental; Modelling	China	Polycrystalline silicon	The tank has a simple open-tank design (with circulating-loop connections)	Temperature stratification can be modelled by dividing water volume (in tank) into layers
Candanedo and Athienitis (2009)	Non-concentrating BIPVT/air: Roof-integrated	Experimental; Modelling	Canada	Not directly stated	More than 22 kW of thermal energy can be recovered by means of 2 heat pumps and stored in a water tank	The active thermal-energy storage system can be charged either by using an air-to-water heat

					with a capacity of 4000 L	exchanger or by means of a heat pump
Andreadis et al. (2013)	Non-concentrating BIPVT/water: Roof-integrated	Modelling	Scotland	Polycrystalline silicon	Optimisation of the system was conducted	Optimal performance of the system: 230 L tank of 1 m height; inlet fluid flow rate of 40 kg/h
Kim et al. (2014)	Non-concentrating BIPVT/water: Roof-integrated	Experimental	Korea	Monocrystalline silicon	A tank of 500 L, an auxiliary boiler, an inverter and a fan-coil unit were used	If the BIPVT temperature is 4^{o}C higher than that of the tank bottom, a circulating pump is switched on
Li et al. (2015a)	Non-concentrating BIPVT/air: Façade-integrated	Modelling	USA	Not directly stated	The installation includes air-to-water heat pump, thermal-energy-storage tank and radiant floor heating	The tank is the heat source of the radiant floor heating; The PVs are combined with unglazed transpired solar collectors
Li et al. (2015b)	Concentrating BIPVT/water: Roof-integrated system with air-gap-lens-walled compound parabolic concentrator	Experimental; Modelling	China	Not directly stated	A tank of 20 L was adopted	Water circulates between the PVs and the storage tank, removing heat from the PVs
Abawi et al. (2016)	Non-concentrating BIPV: Façade-integrated PV panels combined with façade-integrated solar thermal collectors	Experimental; Modelling	Austria	Polycrystalline silicon; Amorphous (semitransparent)	The solar thermal collectors are connected with a water storage tank of 500 L	The tank provides hot water for the façade-integrated solar thermal collectors (for heating)
Delisle and Kummert (2016)	Non-concentrating BIPVT/air: Roof-integrated	Modelling	Canada	Monocrystalline silicon	Scenarios with air-to-water heat exchanger and water tanks were studied	In certain cases, auxiliary heating (when the tank temperature is lower than 55^{o}C) was taken into

						account
Jouhara et al. (2016)	Non-concentrating BIPVT/water: Roof-integrated	Experimental	UK	Not directly stated	The roof was connected to a buffer tank inside the chamber	The system includes heat pump and storage system
Wang et al. (2016a)	Non-concentrating heat-pipe BIPVT with PCM, batteries and water tank	Experimental	China	Polycrystalline silicon	The PVT panel is connected to a storage tank of 80 L	The water temperature of the tank showed a maximum value of 47.23^{o}C (simulated solar radiation: 900 W/m^{2}; water flow rate: 600 L/h); Thermal efficiency: 61.10%
Wang et al. (2016b)	Non-concentrating heat-pipe BIPVT/water: Potential of building integration (walls, roofs, balconies: residential buildings)	Experimental; Modelling	China	Polycrystalline silicon	The system includes a water tank of 80 L for thermal storage and two parallel batteries for electricity storage	The simulations showed that the temperature of the water tank is associated with solar radiation and water flow rate
Hirvonen et al. (2016)	Non-concentrating BIPV with different heating systems	Modelling	Finland	Not directly stated	Several scenarios in terms of the volume and the cost of the tank were evaluated	A large tank stores more energy but it has higher losses
Gautam and Andresen (2017)	Non-concentrating BIPVT/water: Façade-integrated	Modelling	Denmark; Spain	Not directly stated	The tank was modelled as a stratified storage tank with a uniform loss	The tank includes electric auxiliary heater
Asaee et al. (2017)	Non-concentrating BIPVT/water: Roof-integrated	Modelling	Canada	Crystalline silicon	Hot water from the condenser of the heat pump is stored in the water tank	The proposed system offers energy savings and reduction in GHG emissions
Chialastri and Isaacson (2017)	Non-concentrating BIPVT/air: Fenestration	Experimental; Modelling	USA	Silicon	The system includes a heat exchanger, a storage tank with glycol and a water	A charge controller, a battery and connections with the PV modules are included

					pump	
Buonomano et al. (2017)	Non-concentrating BIPVT/water: Roof-integrated	Modelling	Italy	Polycrystalline silicon	Storage-tank volume per m^2 of BIPVT collector was taken into account	The system includes chiller and batteries
Martin-Escudero et al. (2019)	Non-concentrating PV with double-skin façade and air-source heat pump	Modelling	Spain	Amorphous silicon	The air-source heat pump is connected to a thermal storage tank of 3000 L	If the peak thermal demand cannot be covered only by the air-source heat pump, a natural-gas boiler is utilised

2.2.5. BIPV and BIPVT systems with Trombe walls

Trombe walls are passive solar systems. In the literature about BIPV, there are configurations which combine these walls with BIPV modules and south-facing transparent or semitransparent façades. Solar radiation passes through the façade and is absorbed by the wall. Therefore, Trombe walls can be considered as passive thermal-storage systems.

Taffesse et al. (2016) conducted a study about modelling of a semitransparent PVT Trombe wall for thermal heating of a room. It was concluded that an increase in Trombe-wall thickness offers better thermal stability and comfort in the interior space of the room. Taffesse et al. (2016) noted that the proposed model should be experimentally validated (in the case of cold climatic conditions). With respect to nearly zero-energy buildings, Palacios-Jaimes et al. (2017) discussed the combination of BIPV systems with Trombe walls. Moreover, Hu et al. (2017) presented models about BIPV/Trombe walls. In Figure 5 a schematic of a system (integrated on the south wall of a building construction) studied by Hu et al. (2017) is illustrated.

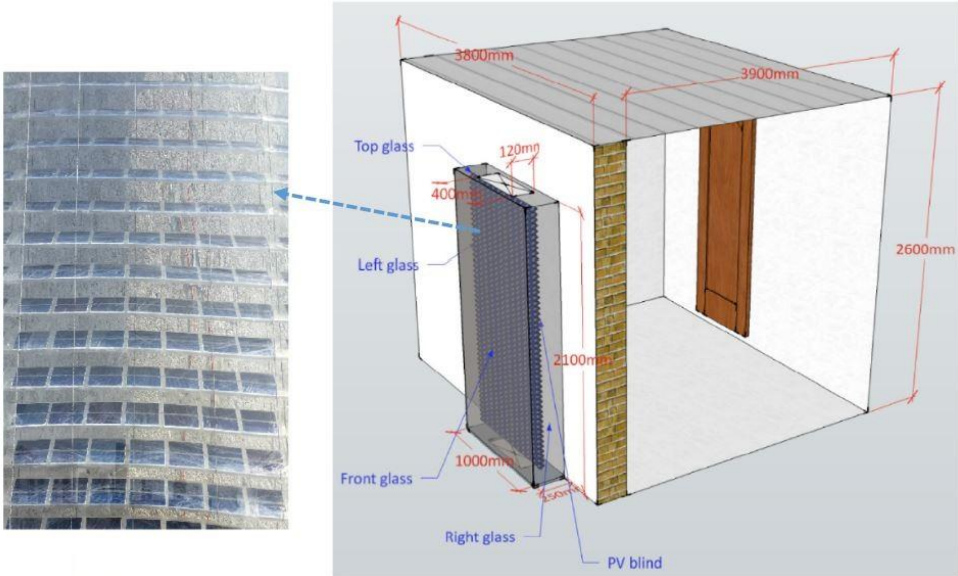

Figure 5. Schematic of a BIPVT/Trombe wall studied by Hu et al. (2017). Source: Hu et al. (2017).

In Table 4, references about BIPV/BIPVT with Trombe walls are presented. From Table 4, it can be noted that:

- A large number of studies combine PV modules with Trombe walls and glass coverings. In this case, there is an air channel between the cover and the PV panels.
- The investigations are modelling and experimental/modelling.
- Different countries/climatic conditions were studied: China, Turkey, Malaysia, India and Algeria.
- A large majority of the studies include silicon-based PV cells.
- Certain investigations place emphasis on the environmental benefits of these types of walls (reduction in CO_2 emissions, etc.) whereas other studies highlight advantages such as PV-output increase (due to ventilation) and wall high capacitance (as solar collector and storage system).

333 **Table 4.** References about BIPV/BIPVT systems with Trombe walls.

Study / year	Type of system	Type of study	Location	Type of PV cells	Information about the wall	Comments
Jie et al. (2007a)	PV-Trombe wall installed in a fenestrated room	Experimental; Modelling	China	Polycrystalline silicon	The proposed system includes: PV/glass panel, black wall/thermal absorber, air duct, air vents	Experimental findings: the daily average PV electrical efficiency can reach the value of 10.4%
Jie et al. (2007b)	Room with PV-Trombe wall	Modelling	China	Not directly stated	A black massive wall is a thermal storage system	The air duct behind the PV panels offers an increase of 5% in PV-cell efficiency
Kundakci Koyunbaba and Yilmaz (2012)	Trombe walls with single-, double-glass and PVs	Experimental; Modelling	Turkey	Amorphous silicon	Semitransparent PVs combined with single- and double-glass	The heat that is stored in the wall during the day is transferred into the interior space of the room/building during night
Kundakci Koyunbaba et al. (2013)	Semitransparent PVs integrated on a Trombe wall	Experimental; Modelling	Turkey	Amorphous silicon	The PVs were integrated on the south façade of a test room; Behind the PVs: 0.5 m of distance and a thermal mass (bricks, polystyrene, plaster)	The proposed system offers environmental benefits in the frame of sustainable buildings
Su et al. (2014)	Built-in PV-Trombe wall	Modelling	Not directly stated	Not directly stated	Model: exterior cover (glass), PV modules attached to the interior absorber wall, air channel	Cooling (by means of natural ventilation) enhances PV output
Irshad et al. (2015)	Different types of glazing (single, double, double filled with gas) combined with PV-Trombe wall	Experimental; Modelling	Malaysia	Polycrystalline silicon	Single-room house with PV-Trombe wall	The storage wall was modelled as a high-capacitance solar collector connected to the room
Taffesse et al. (2016)	Semitransparent PVT Trombe wall	Modelling	India	Semitransparent	Wall materials: brick, cement; Thermal heating of a room	Optimum wall thickness: 0.3-0.4 m; PV packing factor and

						absorptivity influence the thermal stability of the air temperature of the room
Sharma and Kumari (2016)	Naturally ventilated BIPV/Trombe wall	Modelling	Algeria	Silicon-based	The system includes: 1) vertical wall of heavy masonry, 2) two orifices for the circulation of the air between the chimney and the space between the wall and the PVs	The proposed solar wall is effective in terms of building passive heating
Hu et al. (2017)	PV/Trombe wall system	Modelling	China	Polycrystalline silicon	Three configurations (in terms of PV-cell attachment) were examined	The environmental benefits (reduction in CO_2 emissions) of the system were also analysed

2.2.6. BIPV, BIPVT and other kinds of solar systems with multiple types of storage devices

2.2.6.1. BIPVT systems with storage based on pebble beds (or gravel)

In the literature about BIPVT with storage, there are few investigations which present BIPVT with pebble beds (or rocks or gravel) as thermal storage solutions. Kamel et al. (2015) conducted a study about a BIPVT system with air-source heat pump and thermal energy storage (concrete wall/slab; gravel/sand layer; water storage tank). The installation was evaluated in the case of Toronto, in Canada. It was noted that the combination BIPVT/air-source heat pump offers a heating system of high efficiency, especially for harsh winters. Kamel et al. (2015) mentioned that the thermal energy that is produced by the PVT could be stored in a concrete slab (or gravel bed) beneath the floor during day and released during night in order to increase the efficiency of the heat pump.

Ekrami et al. (2015) proposed a BIPVT system which includes air-source heat pump and ventilated sand/gravel bed. Ekrami et al. (2015) noted that the stored thermal energy can be used to preheat the heat-pump inlet air (during cold nights), increasing the coefficient of performance of the heat pump. In addition to this, the heat pump can be utilised for space heating and/or for production of hot water. Scenarios with concrete slab/wall were also examined.

2.2.6.2. BIPVT (and other types of PV systems) with storage based on ice

Tamasauskas et al. (2016) conducted a study about BIPVT systems with heat pump and ice storage. The proposed configuration includes cooling of roof-integrated PV modules and use of the recovered heat in order to supply heating/hot water to the building. A high-performance building, in Calgary and Montreal, in Canada, was investigated. The findings verified that there is a high energy-saving potential. By combining solar collectors, ice heat storage and heat pumps, there is an improvement in terms of the energy-storage densities as well as in terms of the thermal efficiencies of the collectors. Tamasauskas et al. (2016) noted that in the case of the Canadian climate, cold-temperature working fluids could offer advantages such thermal/electrical efficiency enhancement. In the literature about BIPVT, there are few studies which combine BIPVT configurations with ice storage. Investigations about PV systems (not BI) with ice storage have been presented by Xu et al. (2018) and Sehar et al. (2018).

2.2.6.3. BIPV systems with energy storage and smart-grid communication

Sechilariu et al. (2013) investigated a BIPV system for urban areas. The installation includes self-feeding of buildings, storage, DC network distribution, communication with a smart grid and hierarchical control.

In the literature about BIPV, there are few investigations that combine BIPV with smart grids. In this field, additional studies are as follows: Mühlbauer (2017), Wang et al. (2015), Gašparović et al. (2016), project REMOURBAN.

2.2.6.4. BIPV and BIPVT systems which combine different types of storage

Installations which include different kinds of storage devices have been developed and studied. For instance, Chow et al. (2008) investigated a non-concentrating BIPVT/water configuration. The proposed system is façade-integrated and has water storage tank as well as batteries. There is parallel connection of the upper and lower rows of the solar thermal absorbers. In this way, all the collectors take water from the tank at the same temperature. In terms of water circulation, there are two possibilities: 1) with pump and forced circulation, 2) with natural circulation (thermosiphon). The tank has a simple open tank design with circulating-loop connections. The electrical provisions of the PV panels have batteries, inverter as well as connections to the electrical devices.

Another example is the study by Wang et al. (2016a). A non-concentrating heat-pipe BIPVT/water with PCM (paraffin, silica), batteries and water tank was investigated. Metal wires and PCM fill the space between the heat pipes and the insulation material. Furthermore, the PVT panel is connected to a water storage tank of 80 L. Moreover, two parallel batteries are connected to the PVT module.

2.2.6.5. Solar systems with storage based on nanotechnologies

Lightcap and Kamat (2013) evaluated graphene-based nanocomposites for solar energy conversion, storage and sensing. Graphene semiconductor or metal nanoparticle composites are multifunctional materials, useful in the case of energy conversion/storage. These innovations offer advantages such as conversion/storage of solar energy and reduction in the environmental impact. Moreover, these cutting-edge materials include a high degree of structural and composition selectivity. Graphene nanocomposites for sensing can be adopted, for example, in the frame of energy applications based on electronic interactions between semiconductor or metal nanoparticles and graphene (Lightcap and Kamat, 2013).

In the report «Nanotechnology in the sectors of solar energy and energy storage» by Seitz et al. (2013), a whole host of nanotechnologies for energy storage (nanocarbon materials, nanocatalysts, nanoelectrodes, nanocomposites, nanocoatings, etc.) were discussed. For instance, nanocomposites are materials that include the introduction of nanoparticulates into a macroscopic material and can be adopted in the frame of energy storage, solar thermal systems and PV cells. The use of nanocomposites in the case of energy storage offers advantages such as thin and flexible storage devices (Seitz et al., 2013).

In light of the issues mentioned above, in subsection 2.3.2.1 the specific case of micro-/nano-PCMs is discussed. In Table 5, an overview about the storage solutions presented in subsection 2.2.6 is presented.

Table 5. References about BIPV, BIPVT and other kinds of solar systems with multiple types of storage devices.

Storage device	Type of system	References
Pebble beds (or gravel)	BIPVT system with air-source heat pump	Kamel et al. (2015); Ekrami et al. (2015)
Ice storage	BIPVT system with heat pump	Tamasauskas et al. (2016)
Energy storage/smart grid	BIPV with energy storage and smart-grid communication	Sechilariu et al. (2013); Mühlbauer (2017); Wang et al. (2015) ; Gašparović et al. (2016) ; Project REMOURBAN
Combination of different kinds of storage devices	BIPV and BIPVT which combine different types of storage systems	Chow et al. (2008); Wang et al. (2016a)
Nanotechnologies	Solar systems (in general) with storage based on nanotechnologies	Lightcap and Kamat (2013); Seitz et al. (2013)

2.2.7. Agricultural applications: BIPV and BIPVT systems with different kinds of storage devices

In recent years, there has been an increasing interest in BI solar systems in agriculture. Benis et al. (2017) developed a decision support tool for BI agriculture applications in urban environment. Different configurations, including options with PV panels, were examined. Benis et al. (2017) highlighted environmental benefits such as reduction in GHG emissions. Another study is that by Tayab et al. (2017). The adoption of BIPVT configurations in greenhouses was discussed and a literature review about storage devices appropriate for greenhouses was conducted. Furthermore, a classification of passive greenhouses with different kinds of storage systems was presented (Tayab et al., 2017):

- Passive solar greenhouses with water storage (e.g. water in plastic bags placed between the plants).
- Passive solar greenhouses with PCMs (e.g. PCMs placed underground).
- Passive solar greenhouses with buried pipes (e.g. pipes buried in soil).
- Passive solar greenhouses with rock-bed storage (e.g. placed underground).
- Passive solar greenhouses with north-wall storage (e.g. the exterior part of the wall is well-insulated and the interior one is painted in dark colour).

Regarding rock-bed storage, Tayab et al. (2017) noted that rock beds are useful and cost-effective thermal storage systems for solar greenhouses. For instance, a rock-bed with gravel can be placed underground and covered with concrete. During the day the heat from the greenhouse air is stored in the storage device and during the night this heat is utilised.

Additional studies about BIPV and BIPVT systems in the frame of agricultural applications are as follows:

- Assoa et al. (2017) investigated BIPVT for drying systems. An optimised PVT prototype was integrated into the roof of a fodder dryer. Analysis of thermal, electrical and aerodynamic data was done.
- Nayak and Tiwari (2008) conducted an energy/exergy analysis about a PVT system integrated into the roof of a greenhouse. A model was developed and validated with experimental data. Energy savings were also calculated.
- Yano and Cossu (2019) presented an overview about transparent, semitransparent and opaque BIPV configurations for sustainable greenhouses.

2.3. DISCUSSION ABOUT DIFFERENT TYPES OF STORAGE SYSTEMS WITH EMPHASIS ON THEIR ENVIRONMENTAL PROFILE

2.3.1. Batteries

2.3.1.1. General issues about batteries: Environmental, etc.

In the field of PVs for building applications, PV systems can supply electricity for the building and/or the produced electricity can be fed/sold to the grid, depending on the type of the system: On-grid vs. off-grid PV (or PVT) systems. Kalogirou et al. (2014) noted that, in certain cases, on-grid PV systems do not need battery storage and, in addition to this, there is the advantage of higher electricity rates that can be achieved by selling the electricity generated to the grid. However, in the case of off-grid PV (or PVT) systems, batteries play a pivotal role (Lamnatou et al., 2018a). In general, the use of battery storage in residential PVs, offers flexibility because the excess energy output of the PV panels can be stored and supplied during time periods of low or zero solar-energy availability (Oliva et al., 2019). Grid-connected PV systems which include self-consumption are increasingly adopted. In this case, there is use of the electricity produced by the PV installation (mainly for its own functions) and the surplus electricity production is sold to the electricity grid. Moreover, if it is necessary, it is possible to purchase electricity from the grid.

The lifespan of a battery-storage system and, therefore, the replacements of the batteries during the phase of usage, can remarkably affect the environmental performance of the whole system. For the evaluation of the environmental impact of a battery system, data about material manufacturing and life-cycle inventories are critical (Sullivan and Gaines, 2012).

The degradation of the batteries is related to different factors. For instance, in the case of lithium-ion batteries, the degradation is associated with mechanical and chemical issues (Kabir and Demirocak, 2017). Hiremath et al. (2015) studied different types of batteries and recommended the development of batteries which offer high round-trip efficiencies.

Barnhart and Benson (2013) investigated multiple energy-storage technologies: Lithium-ion, sodium sulphur and lead-acid batteries; vanadium-redox and zinc-bromine flow batteries; geologic-pumped-hydroelectric storage; compressed-air-energy storage. Based on energetic-requirement criteria, ranked from the least to the most limited, the options studied showed the ranking as follows: Compressed-air-energy storage, pumped-hydroelectric storage, lithium-ion batteries, sodium-sulphur batteries, vanadium-redox flow batteries, zinc-bromine flow batteries, lead-acid batteries (Barnhart and Benson, 2013). More analytically, based on energy-stored-on-invested (the ratio of the total electrical energy which is stored over the life of a storage device to its embodied primary energy), the results were as follows (Barnhart and Benson, 2013):

- 240 for compressed-air-energy storage.
- 210 for pumped-hydroelectric storage.
- 10 for lithium-ion batteries.

- 6 for sodium-sulphur batteries.
- 3 for vanadium-redox flow batteries.
- 3 for zinc-bromine flow batteries.
- 2 for lead-acid batteries.

In relation to the findings presented above, it should be noted that higher values are less energy intensive (Barnhart and Benson, 2013).

Oliveira et al. (2015) noted that battery-storage systems present higher impacts than mechanical-storage solutions due to their lower number of cycles and life-time energy. Vandepaer et al. (2017) examined the environmental profile of lithium-metal-polymer and lithium-ion stationary batteries. It was found that the phase of manufacturing is responsible for the majority of the environmental impacts. Davidson et al. (2016) evaluated lead-industry life-cycle investigations and it was mentioned that lead is one of the most recycled materials in widespread use.

Concerning end-of-life, all batteries should be properly collected and recycled so as to eliminate the risk of releasing hazardous materials. Waste-battery recycling offers multiple benefits: 1) the negative effect that hazardous waste has on human health and environment is avoided, 2) materials that can be useful for the production of new products are recuperated (Longo et al., 2014).

2.3.1.2. Toxicity of lithium-ion and lead-acid batteries

Lithium-ion batteries play a pivotal role in handheld devices and stationary storage systems. Especially in the case of medium- and large-scale applications, these kinds of storage devices offer high amounts of energy in small volumes. Nevertheless, there are certain environmental issues (safety hazards, toxic gas emissions from damaged lithium-ion batteries, etc.) that should be taken into account (Nedjalkov et al., 2016).

Larsson et al. (2017) investigated heat release and fluoride gas emissions related to battery fires for several kinds of lithium-ion batteries. It was found that considerable quantities of hydrogen fluoride can be produced. Moreover, in certain of the fire tests, amounts of 15–22 mg/Wh of phosphoryl fluoride were measured. In addition to this, Larsson et al. (2017) highlighted that fluoride gas emissions can be a toxic threat, especially in the case of large lithium-ion battery packs.

Nedjalkov et al. (2016) presented measurements of gas emissions from lithium-ion batteries in the case of a malfunction, with emphasis on toxic compounds. Gas chromatography-mass spectrometry, quadrupole mass spectrometry, photoacoustic spectroscopy and chemical analysis were adopted.

Lebedeva and Boon-Brett (2016) examined chemical hazards and risks related to the accidental release of lithium-ion battery electrolyte into an enclosed space, placing emphasis on the inhalation toxicity of certain gases. It was found that, at room temperature, a small electrolyte release can lead to a toxic atmosphere with considerable impacts on human health.

Üçtuğ and Azapagic (2018) conducted an LCA about multi-crystalline PV systems with lithium-ion batteries, for domestic applications. It was found that, on a life-cycle basis, the system produces 4.7–8 times more energy than it consumes. Moreover, it was noted that human toxicity is mainly due to the battery storage (66%).

Lead-acid batteries are widely used in the frame of different applications such as automotive and telecommunication. This means that every year huge amounts of waste batteries are produced (Zhang et al., 2016). In this case, the environmental concerns are related to toxic/flammable substances that can cause fires, explosions and poisoning, with remarkable impact on ecosystems and human health. Zhang et al. (2016) investigated the leakage of electrolyte (mainly sulfuric acid) related to lead-acid batteries. It was found that sulfuric-acid leakage is a major environmental risk of lead-acid batteries during the phases of manufacturing, processing, transportation, use and storage.

Regarding recycling of lead-acid batteries, in the report «Recycling used lead-acid batteries: health considerations» by World Health Organisation (2017), useful information was presented. More analytically, it was highlighted that the exposure to lead from recycling of lead-acid batteries is associated with certain emissions during recycling process. Lead particles and fumes can be inhaled and/or deposited onto surfaces (water bodies, soil, etc.). If there is no appropriate disposal of the lead-processing waste materials, these can contaminate terrestrial and aquatic ecosystems. Furthermore, lead can contaminate food chains (World Health Organisation, 2017).

In light of key issues included in subsections 2.3.1.1 and 2.3.1.2, in Table 6 parameters which influence the environmental profile of battery-storage devices are presented.

Table 6. Factors which are related to battery-storage environmental performance.

Parameters/issues	**References**
Life-cycle inventory; lifespan; replacements of the batteries during the phase of usage	Sullivan and Gaines (2012)
Degradation	Kabir and Demirocak (2017)
Round-trip efficiencies	Hiremath et al. (2015)
Energy-stored-on-invested	Barnhart and Benson (2013)
Number of cycles; life-time energy	Oliveira et al. (2015)
Material manufacturing	Sullivan and Gaines (2012); Vandepaer et al. (2017)
Recycling	Davidson et al. (2016); Longo et al. (2014)
Safety hazards	Nedjalkov et al. (2016)
Battery fires and toxic emissions	Larsson et al. (2017)
Malfunction and toxic compounds	Nedjalkov et al. (2016)
Accidental release of battery electrolyte into an enclosed space; inhalation toxicity of certain gases	Lebedeva and Boon-Brett (2016)

Human toxicity	Üçtuğ and Azapagic (2018)
Toxic/flammable substances; leakage of electrolyte; fires, explosions, poisoning; impact on ecosystems and human health	Zhang et al. (2016)
Recycling and emissions during recycling process; contamination of terrestrial/aquatic ecosystems and food chains	World Health Organisation (2017)

2.3.2. PCMs

2.3.2.1. General issues about PCMs: Environmental, etc.

In the literature about PCMs, there are studies which focus on the application of these materials on the envelope of a building (without including BI solar systems such as BIPV or BIPVT). Panayiotou et al. (2016) investigated macroencapsulated PCM on the envelope of a typical dwelling. The case of Mediterranean climatic conditions (Cyprus) was examined. Simulations in terms of energy rate and temperature were performed. It was found that the use of PCM offers 21.7-28.6% energy savings. Life-cycle cost analysis was also conducted. Panayiotou et al. (2016) noted that the scenario which includes PCM shows a very long Payback Time (PBT) (14.5 years). However, if the PCM component is combined with insulation, the PBT was calculated to be 7.5 years (Panayiotou et al., 2016). Moreover, Athienitis et al. (1997) investigated the thermal performance of a passive solar test-room with PCM wall (butyl stearate). Chwieduk (2013) studied PCM walls in high-latitude countries. Avagliano et al. (2017) presented a model about PCMs for building envelopes. Barzin et al. (2016) investigated PCM gypsum boards for a passive solar building. The results showed remarkable cost and energy savings.

On the other hand, there are studies which include both PCMs and BI solar systems (BIPV, BIPVT, etc.). In Table 2, representative studies about BIPV/PCM and BIPVT/PCM configurations have been presented.

Regarding review articles about PCMs, Fokaides et al. (2015) conducted a critical review about PCMs integrated into transparent building elements. It was noted that, in this case, there are certain barriers. In general, it can be said that PCMs integrated into transparent building components are promising but there are some disadvantages. One of these drawbacks is associated with the change in terms of the transparency of certain PCMs when they change phase. An additional disadvantage is related to the performance of passive PCM systems during long hot days. Another issue is the low thermal conductivity of some PCMs. With respect to aspects for improvement, in the study by Fokaides et al. (2015) several options were discussed:

- More accurate evaluation of PCM performance in real dynamic conditions.
- Development of tools for PCM modelling/simulations and methods which take into account the latent heat loads.
- Economic feasibility of PCM systems.
- Control in terms of PCM flammability.
- Enhancement of PCM thermal-storage capacity by means of encapsulation improvements.
- PCM heat-transfer increase.

Hasan et al. (2010) conducted a study about the evaluation of PCMs for thermal regulation enhancement of BIPV systems. In relation to PCM-based heat-removal techniques in order to reduce PV-panel temperature, it was noted that PCMs present certain advantages (Hasan et al., 2010):

- Higher heat-transfer rates in comparison to forced air (or forced water) circulation.
- Higher heat absorption because of latent heating.

- In the case of passive systems, there is no need for electricity consumption during the phase of usage.
- The heat exchange is passive.
- There is no noise.
- There is no maintenance cost.
- There is on-demand heat delivery.

However, Hasan et al. (2010) highlighted that, in certain cases, PCMs have disadvantages:

- Usually, the cost of PCMs is higher in comparison to forced air (or forced water) circulation.
- Certain PCMs are toxic, corrosive and present fire-safety issues.
- PCMs may have disposal problems (at the end of their life cycles).

In the review article by Sarbu and Dorca (2018), advantages and disadvantages of PCMs were discussed. With respect to organic-PCM drawbacks, flammability, low thermal conductivity and relative large volume change were highlighted. Regarding inorganic-PCM disadvantages, super-cooling and corrosion were mentioned. Concerning PCM encapsulation, Sarbu and Dorca (2018) noted that unless the matrix encapsulating the PCM component presents high thermal conductivity, the micro-encapsulation system has low heat-transfer rate. Enhancement of the heat transfer can be achieved, for instance by means of fins (Sarbu and Dorca, 2018).

Furthermore, Arshad et al. (2019) presented a critical review about the specific case of micro-/nano-PCMs. It was noted that organic PCMs offer benefits such as high phase-change enthalpy but their thermal conductivity is low and, in addition to this, during melting they have leakage. However, the drawbacks mentioned above can be overcome by means of micro- and nano-encapsulation. Arshad et al. (2019) concluded that:

- The encapsulation of organic PCMs with a polymer shell is simple.
- The encapsulation of inorganic PCMs can be difficult and expensive, for instance in the case of hydrophilic salt hydrates.
- There is a need for monitoring the molecular weight of the polymers in shell formation.
- By taking into account all the encapsulation techniques that were examined, in-situ polymerisation was found to be the most effective solution because it offers higher encapsulation efficiency and thermophysical stability.
- Encapsulated PCMs are the most effective for thermal energy storage.

2.3.2.2. Toxicity and payback times of certain PCMs

Lamnatou et al. (2018b, 2018c) presented an LCA study about BIST collectors with/without myristic-acid PCM and rock wool. Energy Payback Time (EPBT) results showed that if the inputs for pumping/auxiliary heating are not taken into consideration, both options with/without PCM have almost the same EPBT (about 1.3 years) (Lamnatou et al., 2018b). The investigation based on ReCiPe, USEtox and Ecological footprint, revealed that, according to ReCiPe endpoint/single-score, ReCiPe endpoint/with characterisation (species.yr), USEtox with characterisation/human toxicity (cancer), USEtox with characterisation/ecotoxicity, the PCM component presents a high environmental impact (remarkably higher in comparison to the other elements of the BIST installation) (Lamnatou et al., 2018c). For the evaluation of the PCM impact, fatty acid (Sources: SimaPro; ecoinvent) is the material that was considered. The production of this acid includes vegetable-origin oils which considerably affect the environmental impact of the final product.

Noël et al. (2015) conducted an LCA about PCMs. It was noted that, in the case of domestic hot water systems, dodecanoic acid which comes from palm kernel oil is a viable PCM because it shows PBTs (in terms of energy and carbon emissions) less than 3 years. Nevertheless, ethyl hexadecanoate produced from algae has high embodied energy and this leads to high PBT (for domestic thermal buffering systems).

In the study by Aranda-Usón et al. (2013), information about the environmental profile of different kinds of PCMs (organic paraffin-based materials; sodium sulphate, water and additive compounds) in the case of buildings in Spain can be found. More analytically, the impact categories of marine eutrophication, freshwater eutrophication, terrestrial acidification, particulate matter formation, human toxicity, ozone depletion and climate change (ReCiPe method) were examined. The LCA results showed that the environmental profile of a certain configuration depends on the climatic conditions and the type of the PCM used.

López-Sabirón et al. (2014) investigated PCMs for industrial applications. A thermal-energy-storage system with PCM (sodium nitrate) and heat-transfer fluid (commercial synthetic thermal oil: biphenyl/diphenyloxide eutectic mixture) was examined, based on LCA. The phases of material manufacturing, usage and end-of-life were taken into account. The methods CML 2001 and Eco-indicator 99 were adopted. By placing emphasis on the thermal-energy-storage manufacturing, even if PCM presented the highest impact in almost all the midpoint impact categories, the heat transfer fluid showed higher impact in terms of human toxicity. Nevertheless, the PCM presented the highest contribution (around 76%) in terms of the total $CO_{2.eq}$ emissions. Diphenyl ether is the major component of the heat-transfer fluid which was considered for the thermal-energy-storage system (López-Sabirón et al., 2014).

In light of the factors discussed in subsections 2.3.2.1 and 2.3.2.2, in Table 7 key issues which influence the environmental profile of PCM-storage devices are presented.

Table 7. Factors which are related to PCM-storage environmental performance.

Parameters/issues	**References**
Several types of PBTs for systems with PCMs	Noël et al. (2015); Panayiotou et al. (2016)
Thermal performance of a room with PCM	Athienitis et al. (1997)
PCM walls in high-latitude countries	Chwieduk (2013)
PCMs for building envelopes	Avagliano et al. (2017)
PCM boards for passive solar buildings	Barzin et al. (2016)
The performance of passive PCM systems during long hot days; low thermal conductivity of certain PCMs	Fokaides et al. (2015)
Certain PCMs are toxic, corrosive and have fire-safety issues and disposal problems (at the end of their life cycles)	Hasan et al. (2010)
Flammability; corrosion	Sarbu and Dorca (2018)
Phase-change enthalpy; leakage; encapsulation	Arshad et al. (2019)
EPBT; human toxicity; ecotoxicity	Lamnatou et al. (2018b, 2018c)
PCMs in buildings: the environmental profile depends on the climatic conditions and the type of the PCM	Aranda-Usón et al. (2013)
Human toxicity and $CO_{2.eq}$ emissions	López-Sabirón et al. (2014)

2.3.3. Water storage tanks: Embodied energy, embodied carbon, toxicity

With respect to thermal energy storage technologies, Palomba and Frazzica (2019) presented a critical review about key performance indicators classified into four categories:

- Technical requirements.
- Socio-economic parameters.
- Environmental aspects.
- Safety issues.

Thermal energy storage systems based on water storage tanks have been widely used in the case of BA solar thermal collectors for buildings. Thermosiphon (natural circulation; passive) solar water heating installations are the simplest solar-energy collection devices. They supply hot water for domestic applications at a temperature of approximately 60^{o}C and include BA solar thermal collectors, storage tanks and tubes (Kalogirou, 2009). Moreover, in the case of BIPVT (especially when the working fluid is water), studies with water storage tanks have been presented (Table 3).

In the literature about LCA on solar thermal collectors and PVT, the environmental profile of water storage tanks has been discussed. In Table 8, selected references are presented. From Table 8, it can be seen that, in the frame of LCA studies about different kinds of solar systems (Building-Added Photovoltaic/Thermal (BA PVT), BIPVT, flat-plate solar thermal collectors), the impacts of water storage tanks have been evaluated. Concerning the sources of data, SimaPro software and ecoinvent database were used. The volumes of the tanks are as follows: 300 L and 600 L. The impacts that were calculated range from 5.9 to 11.7 GJ_{prim} and from 0.3 to 1.0 t $CO_{2.eq}$, depending on the scenario.

Table 8. Literature references with information about the environmental profile of water storage tanks.

Reference	**Type of system**	**Capacity of the tank**	**Environmental profile of the tank**	**Sources of data for the calculation of the environmental impacts**
de Laborderie et al. (2011)	Flat-plate solar thermal collectors	300 L	7.5 GJ_{prim} (approximately) (non-renewable primary energy) 0.4 t $CO_{2.eq}$ (approximately)	Software: SimaPro 7 Database: ecoinvent 2
Sun (2014)	BIPVT	600 L	8.6 GJ (cumulative energy demand) 0.7 t $CO_{2.eq}$ (IPCC 2013 GWP 100a)	Software: SimaPro Databases: ecoinvent
Lamnatou et al. (2018a)	BA PVT	300 L	5.9 GJ_{prim} (cumulative energy demand) 0.3 t $CO_{2.eq}$ (IPCC 2013 GWP 100a)	Software: SimaPro 8 Database: ecoinvent 3

SimaPro 8; ecoinvent 3	Hot water tank	600 L	11.7 GJ_{prim} (cumulative energy demand) 1.0 t $CO_{2.eq}$ (IPCC 2013 GWP 100a)	Software: SimaPro 8 Database: ecoinvent 3

By placing emphasis on the toxicity of these storage devices, according to SimaPro 8 and ecoinvent 3, for a hot water tank of 600 L capacity the results are as follows:

- 329.5 kg 1,4-DB eq: Human toxicity, ReCiPe midpoint with characterisation.
- 0.1 kg 1,4-DB eq: Terrestrial ecoxicity, ReCiPe midpoint with characterisation.
- 33.8 kg 1,4-DB eq: Freshwater ecoxicity, ReCiPe midpoint with characterisation.
- 33.8 kg 1,4-DB eq: Marine ecoxicity, ReCiPe midpoint with characterisation.
- 0.0002 DALY: Human toxicity, ReCiPe endpoint with characterisation.
- 1.9E-08 (species.yr): Terrestrial ecotoxicity, ReCiPe endpoint with characterisation.
- 2.9E-08 (species.yr): Freshwater ecotoxicity, ReCiPe endpoint with characterisation.
- 6.0E-09 (species.yr): Marine ecotoxicity, ReCiPe endpoint with characterisation.
- 2.3E-07 CTU_h: Human toxicity/cancer, USEtox with characterisation.
- 1.6E-09 CTU_h: Human toxicity/non-cancer, USEtox with characterisation.
- 4.6 CTU_e: Ecotoxocity, USEtox with characterisation.

Finally, it should be noted that, in the frame of LCA of solar systems for buildings, for the evaluation of the environmental impact of a water storage tank, the materials/components that could be taken into account are as follows: Copper heat exchanger, stainless steel, polyurethane foam or rock wool, plastics (Lamnatou et al., 2018a, 2019). In terms of water-storage-tank replacement during the phase of usage, for a domestic solar system with a lifespan of 20-30 years, one replacement of the tank could be assumed (Lamnatou et al., 2019).

3. CONCLUSIONS

By taking into account that in the literature about PVT, the majority of the review articles are not for a specific type of solar systems, the present article is an overview about storage options suitable for BIPV and BIPVT applications, with emphasis on environmental issues such as toxicity. The literature review shows that:

- There are multiple storage solutions, appropriate for BIPV and BIPVT applications, based on different kinds of materials (PCMs, batteries, nanotechnologies, etc.).
- In terms of BIPV and BIPVT systems with battery storage, most of the systems are non-concentrating, façade- or roof-integrated, water-based (in the case of BIPVT) and include polycrystalline-silicon PV cells and lead-acid or lithium-ion batteries. Factors such as battery aging, economic/environmental issues and battery capacity were discussed.
- Concerning BIPVT and BIPVT with PCMs, a large majority of the systems are non-concentrating, façade-integrated, air-based (in the case of BIPVT) and consist of silicon-based PV cells and paraffin- or salt-based PCMs. Critical parameters such as thermal regulation, PCM thermal mass, PV/PCM thermal conductivity, PV output and building energy consumption were examined.
- Regarding BIPV and BIPVT with water storage tanks, some studies place emphasis on the installations (storage tanks in combination with heat exchangers, heat pumps, etc.) whereas other investigations focus on building energy needs, energy savings and environmental benefits. In terms of the type of systems, the majority of the references are about non-concentrating, water-based (in the case of BIPVT), façade- and roof-integrated configurations with silicon-based PV cells.

- With reference to BIPV and BIPVT with Trombe walls, a large number of studies combine PV modules with Trombe walls and glass coverings. In this case, there is an air channel between the cover and the PV panels. Regarding PV-cell material, in most of the cases silicon-based PV cells were adopted. Concerning the studied issues, some investigations place emphasis on BIPV/Trombe wall environmental benefits while other references highlight advantages such as PV-output increase and Trombe-wall high capacitance as a storage system.
- In the literature about BIPV, BIPVT and other kinds of solar systems, there are studies which propose the adoption of storage options such as pebble beds, ice, nanotechnologies as well as combination of different kinds of storage devices (batteries, storage tanks, PCMs, etc.). Moreover, certain references place emphasis on the adoption of BIPV and BIPVT systems, based on multiple types of storage solutions, in the frame of agricultural applications (greenhouses, dryers of agricultural products, etc.).
- With reference to factors that influence the environmental profile of storage systems, in the case of batteries some critical parameters are as follows: Life-cycle inventory, phase of material manufacturing, lifespan, round-trip efficiency, replacements during the phase of usage, degradation, end-of-life management and recycling. Regarding PCMs, there are certain materials that are corrosive and present fire-safety issues and disposal problems (at the end of their life cycles). Concerning water storage tanks, based on certain literature references for tanks with volumes of 300 L and 600 L, their impacts range from 5.9 to 11.7 GJ_{prim} and from 0.3 to 1.0 t $CO_{2.eq.}$

- By placing emphasis on the toxicity of certain storage materials, it can be seen that:
    - In the case of batteries, issues such as emissions related to battery fires, malfunction and toxic compounds, accidental release of electrolytes, inhalation toxicity, impact on human health, end-of-life management, flammable and toxic elements that can cause explosions and poisoning, contamination of terrestrial/aquatic ecosystems and food chains should be taken into account.
    - Regarding PCMs, there are investigations which highlight the toxicity of certain PCMs (in terms of human toxicity and ecotoxicity) based on different life-cycle impact assessment methodologies and approaches (midpoint, endpoint).
    - Concerning storage tanks and according to SimaPro 8 and ecoinvent 3 database, a hot water storage tank of 600 L capacity based on USEtox with characterisation presents 2.3E-07 CTU_h human toxicity/cancer, 1.6E-09 CTU_h human toxicity/non-cancer and 4.6 CTU_e ecotoxocity.

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